

# **HOW DO SAFETY MANAGEMENT POLICIES CASCADE DOWN THROUGH AN ORGANISATION TO AFFECT THE INCIDENCE OF MAINTENANCE ERRORS?**

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## **1. Introduction**

There is increasing emphasis by regulators on the use of formal safety management systems (SMS) in the context of aviation maintenance. However, there is little agreement about the nature of such systems, and how they might actually exert the desired affect of reducing the incidence of maintenance errors. In order to gain insights into the ways in which SMS systems may be made as effective as possible, it is necessary to develop tools and techniques that allow us to explicitly map the routes via which SMS might exert their effects in real organisations.

In this paper, an approach will be described, called IDEAS (Influence Diagram Evaluation and Assessment System) that can achieve this objective. In addition to aviation maintenance, this approach has been applied to a number of industrial domains including railways, nuclear power generation, cockpit errors and marine transport. IDEAS has a number of important applications in improving the safety and reliability of aircraft maintenance. Firstly, it provides an explicit and easily understandable model of both the direct and indirect factors that influence the reliability of maintenance. This is based upon a combination of information from all available sources, including research studies, incident reports and the insights of personnel actually engaged in maintenance operations at the ‘sharp end’. This provides comprehensive and practical insights into the factors that influence maintenance reliability.

The structure of the model and the factors that it contains provide the basis for performing causal analyses of maintenance incidents, which explicitly include the effects of organisational and other ‘latent system causes’ of failures (Reason, 1997; Maurino et al, 1995). The model can provide the basis for the proactive evaluation of an existing maintenance system at the levels of individual maintenance teams, aircraft or individual maintenance tasks. This form of evaluation can be used to identify areas of strengths and weaknesses, and to specify the changes that need to be made. This can be extended to quantitatively assess the cost effectiveness of alternative error reduction strategies. The link with SMS means that the management system that has the responsibility to implement and monitor these changes can be explicitly identified, allowing responsibilities for implementation to be assigned.

The first section describes the Influence Diagram concept, which forms the basis for the IDEAS methodology. An application of IDEAS to an aircraft maintenance system is then described, and a simplified version of the resulting model developed, to illustrate how factors at various levels of the maintenance system can affect maintenance errors at the operational level. The application of the model to the analysis of the underlying causes of maintenance incidents will then be illustrated. Finally, the proactive

application of IDEAS to develop an audit tool for assessing an existing aviation maintenance system will be described.

## **2. Influence Diagrams: The basis for the IDEAS Approach**

Influence Diagrams were originally developed at the Stanford Research Institute (Miller et al, 1976) to represent the dependencies between events in terms of conditional probabilities. Their first application was in supporting communications in group decision making by non-specialists in areas such as the siting of hazardous waste repositories (Merkhofer 1990). They were subsequently applied to human reliability analysis in the nuclear power industry (Phillips et al. 1990), to the modelling of major disaster causation (Embrey 1992), and to the assessment of the causes of signals passed at danger in the rail sector (Wright et al. 2000).

### **2.1 Performance Influencing Factors**

In order to understand how Influence Diagrams work, consider an event such as 'Probability of failing to correctly re-assemble a critical component during maintenance'. This will depend on the states of a number of other variables (referred to as Performance Influencing Factors) in the situation, and is therefore a *conditional probability*. In subsequent discussions, bold italics will be used to refer to these factors. The factors that could directly influence the failure probability might include the following:

*Quality of the maintenance tools available*  
*Technical competence of the maintainer*  
*Amount of time pressure*  
*Quality of the procedures and job aids available*  
*Fatigue*  
*Task characteristics predisposing to errors*

The states of each of these Performance Influencing Factors are in turn dependent on other 'sub-factors'. For example, the state or quality of the factor *task characteristics* can be broken down into the following sub-factors:

- *Number of isolated steps* (isolated steps are known to be vulnerable to omissions)
- *Similarity to other tasks* (tasks which are identical apart from a few steps may become interchanged, particularly if one task is performed much more frequently than the other, and there are distractions when the infrequent task is performed)
- *Stability of task method* (maintainers may not be informed of all changes, and may omit or incorrectly sequence the new steps)
- *Complexity* (Complex tasks, e.g. more branches, more steps are more likely to be informed correctly)
- *Design of aircraft for maintainability*. This factor can be broken down into further sub-sub factors as follows:
  - *Component design*
  - *Accessibility of components*
  - *Amount of component removal required*

The Influence Diagram is usually developed and represented in a graphical format. In Figure 1, some of the sub-factors underlying the direct factor *task characteristics* have been shown. Although the Influence Diagram may seem complex, this is simply a reflection of the fact that the likelihood of maintenance errors occurring is potentially influenced by a large number of factors. During the initial construction of the diagram, it is important that as many as possible of the potentially important Performance Influencing Factors are captured, in order to ensure completeness.

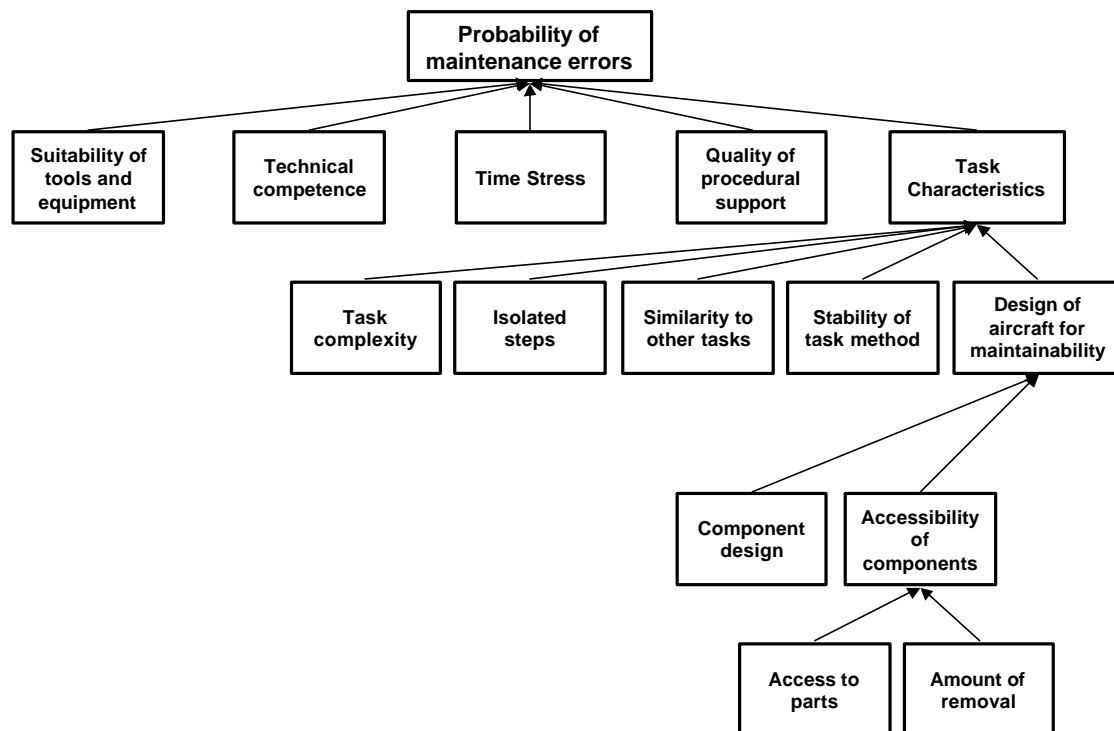


Figure 1: Influence Diagram breakdown for Task Characteristics

Subsequently, it is usually possible to simplify the diagram, by eliminating factors that have an insignificant impact, relative to other factors at the same level. One of the major benefits arising from breaking down factors into sub-factors is ease of assessment. Because many of the factors that directly influence maintenance performance are multifaceted, as shown in Figure 1 for intrinsic *task characteristics*, it would be extremely difficult to make an assessment without first identifying the component sub-factors.

If factors can be assessed for a particular maintenance task at the bottom level of the diagram, it is possible to evaluate whether the factors at the top will be positive or negative in terms of their effects on errors. For example, if all the sub-factors relating to the factor *task characteristics* (*task complexity*, *presence of isolated steps* etc.) were near to the ideal, then the task would be less subject to maintenance error than another task where all these factors were nearer to the 'worst case' situation, (e.g. many isolated steps, task method changed frequently, and inaccessible components). A similar argument can be applied at any level of the factors that influence the overall maintenance performance. Thus, all the factors directly influencing maintenance

performance (*quality of the tools available, technical competence of the maintainer, amount of time pressure*, etc.) could each be broken down to the sub-factors that influence their state.

## 2.2 Links with Management Issues

In Figure 2, the Influence Diagram is developed further to represent the sub-factors underlying two other Performance Influencing Factors: *suitability of tools and equipment* and *time stress*.

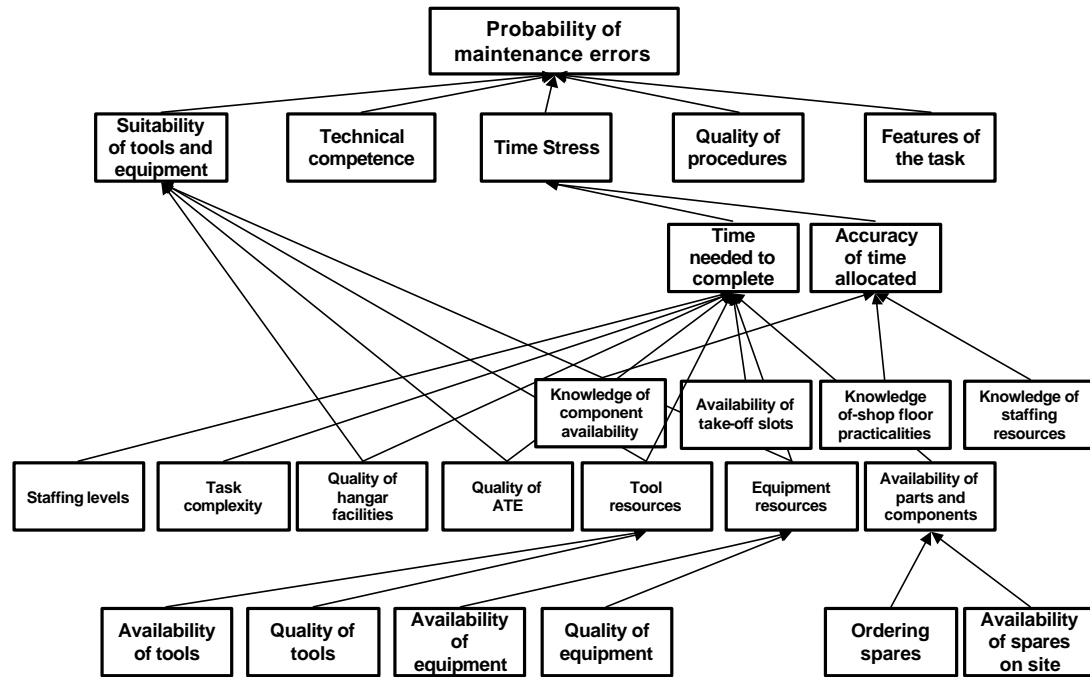


Figure 2: Influence Diagram for Suitability of Tools & Equipment and Time stress

The Influence Diagram is capable of modelling quite complex interrelationships between management strategies and the effects of these strategies on error likelihood. For example, it is widely accepted that time stress, in the form of inadequate time to perform a maintenance operation, is a major contributor to maintenance error. In the Influence Diagram, the *time stress* experienced by a maintainer is influenced by two major factors, the *time needed to complete the task* and *quality of work scheduling* (i.e. the accuracy with which time is allocated by the scheduler (usually a supervisor or manager) to the task. The diagram indicates that this in turn is influenced by factors relating to the experience of the scheduler, i.e. knowledge of component availability, staffing resources, and of the practicalities at the shop floor level of carrying out the task. In addition, certain objective factors, such as the availability of take-off slots, will also influence the likelihood that adequate time is allocated for the task to avoid time stress.

As a result of developing the Influence Diagram structure, the factors that will need to be optimised to support effective scheduling can be identified. The extent to which they are adequately addressed in a specific organisation provides information regarding the

effectiveness of the Safety Management System. This application of the methodology will be discussed in more detail in Section 4.2.

## **2.3 Multiple Pathways**

Another useful feature of the Influence Diagram analysis is that it reveals the presence of certain factors that influence a number of other factors. In Figure 2 for example, it can be seen that the factors *quality of hangar facilities*, *quality of aviation test equipment (ATE)*, *tool resources* and *equipment resources* influence both the *time taken to complete task* and the *suitability of tools & equipment*. This structure arises because these three factors can influence the likelihood of error by two routes. The first route is by affecting the time available to perform tasks. The unavailability of suitable tools and equipment will usually extend the time taken to carry out a job, and hence time stress is likely to arise given that the time already allocated to a job is difficult to extend. Unavailability of tools and equipment will also affect error rates directly, because the task will be more difficult to carry out and hence more error prone. This influence is mapped by means of the links that go directly from the *suitability of tools and equipment* factor. Another factor that affects error probability via two routes is *task complexity*. The diagram in Figure 1 shows that this affects the error probability directly via task characteristics as well as affecting the length time taken to carry out the task.

Generally speaking, the larger the number of links that emanate from a factor, the greater its influence is likely to be. In reliability engineering, such factors are sometimes referred to as ‘Common Causes’, and are regarded as being particularly difficult to model. The ability of the Influence Diagram to identify and model the effects of these common causes is one of its major advantages.

## **3. Developing the Influence Diagram**

The Influence Diagram provides a method for acquiring information from a wide variety of sources in order to develop a comprehensive and realistic model of the direct and indirect causes of maintenance errors for organisation of interest. Any particular model is likely to include both organisation specific and generic factors. In general, it is advisable to tailor any generic model to take into account the specific factors in an organisation. The development of the model comprises three stages:

- Development of a preliminary Influence Diagram model based on previous research findings and incident analyses
- Interactive sessions to tailor the preliminary model to the specific organisation
- Evaluation of the relative importance of the factors in the model in terms of their impact on maintenance error
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### **3.1 Development of the Preliminary Influence Diagram**

The first stage involves reviewing the available human factors research and any information from incident analyses. A preliminary Influence Diagram is then developed by the analysts using a computer program called IDEX (Influence Diagram Expert). This allows the diagram to be developed in a graphical format, using the

comprehensive editing facilities available in IDEX. These facilities allow the structure of the diagram to be easily changed, and for additional information regarding the factors to be stored in a database.

### **3.2 Tailoring the Diagram to the Organisation**

The next stage consists of a series of interactive sessions with individuals with direct experience of the organisation. The purpose of these sessions is to gain feedback regarding the comprehensiveness and validity of the initial diagram and to modify and extend it to reflect the perceptions of the participants. The interactive session is carried out using the IDEX software and a data projector, which allows the participants to easily modify the structure of the diagram in response to the discussions. Ideally, the participants should represent as wide a range of experience as possible, and should include the people who will be affected by any decisions arising from the study. This develops a sense of ownership in the model, rather than it being seen as being imposed by ‘outsiders’. The participants should include managers and supervisors as well as technicians, to ensure that all perspectives are represented.

### **3.3 Evaluating the Relative Importance of the factors**

Initially, the structure of the Influence Diagram only indicates that certain factors, e.g. *technical competence*, *time stress* have *some influence* on other factors, e.g. the probability of error. In the final stage of developing the Influence Diagram, the relative strength of the influences is assessed. These assessments are made on the basis of the experience of the participants in the IDEAS session, together with any objective data that may be available. Once they have been completed, assessments of the quality of the factors at the bottom level of the diagram can then be propagated upwards to give a single index at the top of the tree. This is a measure of the quality of the conditions influencing the reliability of maintenance. This index ranges between 0, for worst-case conditions to 1, for best attainable conditions. The closer it approaches this ideal value, the lower the probability of maintenance error is likely to be.

The Influence Diagram therefore provides a method for aggregating together the complex set of factors that influence maintenance error in an organisation into a single number. It also allows the effects of changing different factors to be investigated. For example, if an improvement in *staffing levels* produces a 20% decrease in expected maintenance errors, whereas a change in *quality of equipment* only produces a 5% change, then the former change should be chosen (assuming they both cost the same to implement). The IDEAS model therefore provides a basis for the cost effectiveness evaluation of alternative improvement strategies.

## **4. Applying IDEAS**

The Influence Diagram approach in the form of the IDEAS methodology can be applied both proactively and retrospectively to reduce the likelihood of maintenance errors. In this section three main application areas are described:

- Providing a framework for identifying the underlying causes of incidents that have already occurred, and prescribing cost effective preventative strategies

- As a general modelling tool to understand the structure of the underlying causes of maintenance errors in an organisation, and assigning responsibilities to the various components of the Safety Management System to control these causes.
- Providing the basis for audit tools that identify the vulnerable areas in an organisation and provide guidance with regard to how these vulnerabilities are to be addressed

#### **4.1 Use of IDEAS in the causal analysis of incidents**

Most incident investigation processes devote the majority of their resources to the delineation of *what* happened, i.e. to establishing the exact sequence of events in the incident. In general, there is considerably less effort spent on establishing *why* the incident occurred. This is because many organisations have a strongly held belief that errors arise primarily from the individual failings or inadequacies of maintenance technicians. From this perspective there is little motivation to spend time in establishing underlying causes, apart from identifying possible random hardware failures that could have given rise to the incident. Thus, the analysis of causes often tends to focus on failings of the individual maintainer such as lack of knowledge, lack of diligence or application, or deliberate violations of rules or procedures in order to make the job easier. However, an alternative to the individually focussed view of accident causation exists.

The Systems View, whilst accepting that these individual causes will certainly be implicated in some incidents, tries to identify the broader range of factors that can have an impact on maintenance error. It will be apparent that the IDEAS approach is based upon the Systems philosophy. The Influence Diagram is designed to develop a comprehensive model of the factors (and their interrelationships) that may be acting together to influence the likelihood of error. Some of the factors identified in the model are common to the individual centred approach of traditional accident investigation, whereas others address the precursors of conditions (e.g. time stress) that may have a direct impact on maintenance reliability.

The structure of the Influence Diagram developed by IDEAS provides the basis for a series of questions which first identify the direct causes (or Performance Influencing Factors), and then the underlying causes that could have given rise to the direct causes. For example, consider a specific incident where a critical component has been omitted. For the purpose of this example, we shall assume that the Influence Diagram set out in Figures 1 and 2 contains all the factors relevant to this incident. The first stage of the investigation would include the usual gathering of information to establish what happened.

The structure of the incident investigation would be based on the Influence Diagram and would consist of the following stages:

##### ***4.1.1. Establishing direct causes***

The first questions would establish whether one or more of the direct Performance Influencing factors were implicated in the incident:

Did any of the following conditions influence the occurrence of this incident?

- Suitability of tools and equipment?

- Technical competence of the technician?
- Time stress?
- Quality of the procedures?
- The nature of the task?

In response to these questions, the answers might be: Factors A, B, C, etc were strongly implicated, weakly implicated, or not known. In the latter case, judgement would be suspended until questions were asked at the next level of detail. For example, it might not be clear initially if the suitability of tools or equipment was a factor in the component being omitted. However, the questions posed at the next level concerning the hangar facilities, tool resources and quality of the ATE will enable the investigator to assess the adequacy of the maintenance system from this perspective, and assist in identifying whether this was a factor in the specific incident.

#### ***4.1.2. Establishing underlying causes***

This process of successively moving down the Influence Diagram continues until the underlying causes are established. These will normally be at the bottom level of the diagram. For example, if one of the direct causes of the omitted component was *time stress*, the ultimate cause may be a combination of lack of knowledge of the shop floor practicalities and the unavailability of staffing resources by the scheduler.

#### ***4.1.3. Developing preventative measures***

Once the causal analysis has proceeded to the bottom level of the Influence Diagram for the factors that are implicated in the incident, the basic root causes will have been established. These deficiencies will then need to be remedied. In the example cited above, the inadequate *knowledge of shop floor practicalities* and *staffing resources* could be remedied by ensuring that schedulers have regular contact with shop floor operations, and effective communication systems to provide information on current personnel resources.

#### ***4.1.4 Identifying Safety Management implications***

The identification of fixable root causes by the IDEAS process allows the responsibilities for ensuring that these conditions do not arise in the future to be assigned to the appropriate area of the Safety Management System and the individuals tasked with this responsibility. This issue will be explored further in section 4.2.

#### ***4.1.5. Updating the model***

In the event that a new Performance Influencing Factor, not included in the existing Influence Diagram model, is identified as contributing to the incident, this is added to a list of possible factors that may subsequently be used to update the model. In this way, the model of error causation encapsulated in the original Influence Diagram will be constantly updated based on experience. The frequency with which the factors in the model occur provides an indication of the relative weights of these factors in terms of their impact on error causation. These can be compared with the weights originally assigned by the expert group when developing the original diagram, and updated if necessary.



#### ***4.1.6 Benefits of using IDEAS to support the investigation of underlying causes***

The use of the IDEAS methodology to structure the investigation of underlying causes provides a number of specific benefits.

The existence of an explicit model of error causation provides a framework that generates specific questions that can be asked during the accident investigation process to establish causes. This supports the investigation of incidents in a standardised and consistent manner, and enables information to be aggregated across a number of incidents to allow recurrent root causes to be identified. This in turn provides information regarding which of these causes should have the greatest priority in terms of expenditure of resources to reduce the incidence of errors.

The hierarchical structure of the IDEAS model means that the analyst does not have to consider every possible underlying cause. Certain classes of causes can be eliminated early in the investigation process, thus reducing the amount of resources required to investigate the incident. Because causes are broken down into their contributory Influencing Factors at each level of the analysis, it is easier to prescribe specific preventative measures

The error causation model also encourages the investigator to consider a wider range of potential causes than the traditional individually centred approach. It emphasises that fact that errors may arise from a combination of more than one cause, thus reducing a premature focus on a single cause.

#### **4.2 Using IDEAS to provide inputs to the Safety Management System**

IDEAS identifies the network of influences that affect the likelihood of maintenance errors. This structure is established using all available sources of information, including research data, incident analysis, and most important of all, inputs from people who know the system. The results of the IDEAS analysis should therefore be able to identify the key aspects of the maintenance system that have an impact on maintenance reliability. In particular, IDEAS is able to identify the powerful ‘common cause’ influences that have multiple connections with, and therefore influences on, many aspects of system operation. The information provided by the IDEAS process can assist the Safety Management System by identifying the specific ‘levers’ that will have the major effects on the reliability of maintenance.

<b>Factors Influencing Time Stress</b>	<b>Factors Influencing Suitability of tools &amp; equipment</b>	<b>Management responsibilities</b>
Staffing levels		Personnel/Human Resources
Task complexity		Aircraft manufacturer/design
Quality of hangar facilities	Quality of hangar facilities	Facilities management
Quality of Aviation Test Equipment/tools/other equipment	Quality of Aviation Test Equipment/tools/other equipment	Equipment Procurement

Availability of tools/equipment	Availability of tools/equipment	Equipment resource allocation/management
Spares ordering/availability		Spares Procurement
Availability of take-off slots		Outside the direct control of the management system
Knowledge of component availability		Communication systems
Knowledge of shop floor practicalities		Training/ communication systems
Knowledge of staffing resources		Communication systems

Table 1: Management functions involved in quality of factors influencing maintenance error

The Influence Diagram in Figure 2 identifies Time stress as a factor directly affecting the probability of maintenance error. The IDEAS analysis indicates that *time stress* is actually influenced by a wide range of ‘bottom level’ factors. Once these factors have been identified, the Safety Management System responsibilities for ensuring that they are optimised can be assigned.

Table 1 tabulates some of the management functions that would be involved in ensuring that *time stress* was minimised. The structure of the Influence Diagram shows that some of these factors will have a greater effect than others on the likelihood of both *time stress* and *suitability of tools and equipment*. This information can be used to ensure that the Safety Management System adequately addresses the most important drivers of maintenance reliability. The mapping of management control functions on to the underlying causes of maintenance errors also shows that certain factors, e.g. the *availability of take-off slots*, are not under the direct control of the management system.

Most safety management systems emphasise the importance of both risk analysis and the monitoring of feedback from incident reports to ensure that the System is performing effectively (Mc Donald et al 2000). Using IDEAS for the analysis of incidents allows a more precise identification of underlying causes by specifying the factors that control risk.

#### **4.3 Using IDEAS to develop an audit tool**

Since the influence Diagram provides a link between the attributes of an organisation that can be measured, and the expected probability of error, it provides the basis for developing a maintenance system audit tool. The factors at the bottom of the Influence Diagram can be assessed using appropriate scales and the results of these inputs can be used to provide an index that is related to the probability of failure.

One advantage of developing an audit tool based on the IDEAS Influence model is that it is able to indicate the expected effects on maintenance reliability of making improvements to any problem areas identified in the assessment. It therefore provides immediate guidance with regard to the most effective intervention. Another advantage is the fact that the Influence Diagram can be tailored to include any system specific

factors that may not be included in a more generic tool such as MEDA. An example of some questions developed for the factor *time stress* is shown in Table 2.

Question		1	2	3	4	5	6	Information
49	The process for ordering spares works effectively							An inadequate system would mean a long complex request process, long time to get spares and inaccuracies in the parts eventually obtained.
50	A good knowledge of task duration is always shown in the work schedules							Lack of knowledge about the length of time that tasks will take to complete will lead to unrealistic work schedules.
51	Work schedules always appear to take shop floor practicalities into account (e.g. staffing levels, availability of parts, tools, equipment)							Insufficient consideration of working constraints will mean that the time schedules to complete a task will be unrealistic.

Key: 1= Strongly disagree  
2 = Disagree  
3 = Slightly disagree

4 = Slightly agree  
5 = Agree  
6 = Strongly agree

Table 2: Example of audit tool questions based on IDEAS model

## 5 Conclusions

The IDEAS methodology provides a structured and systematic methodology for identifying the direct and indirect causes of maintenance errors. It has been successfully applied in a number of industries and is now being used to improve flight safety by reducing the likelihood of maintenance errors. It has a number of benefits as a tool for developing a comprehensive model of the factors influencing errors:

It allows insights from a number of sources, including the individuals who work in the system, to be amalgamated together in an externally verifiable form to show the contribution

It allows technical, organisational and cultural factors to be considered within the same framework

It allows cross linkages between factors that affect error in different ways to be identified

The approach has a number of applications. One of the most significant of these is as a method for standardising the investigation of incidents and near misses. By providing a consistent but updateable model of incident causation developed using IDEAS,

investigators are prompted to consider the underlying as well as the direct causes of accidents. The model also helps to combat the tendency to assign a disproportionate amount of emphasis to individual rather than system causes. It emphasises the need to consider the fact that most incidents arise from the combination of more than one cause.

In the area of Safety Management Systems, the IDEAS approach identifies the factors that need to be under the control of the Safety Management System. It is also useful in supporting the risk identification and monitoring aspects of the system, by means of the improved capability to identify the underlying causes of incidents discussed above. The ability of IDEAS to develop a numerical relationship between changes in the factors controlled by the Safety Management System and the probability of maintenance errors means that decisions regarding the best use of resources to minimise risks could be made on a rational and auditable basis.

The identification by IDEAS of the links between aspects of the maintenance system and the likelihood of error provides a good basis for an audit system to identify any weaknesses that might exist. A comprehensive audit tool based on the IDEAS methodology is being developed and tested as part of a current project.

## References

- Embrey, D.E. (1992) *Incorporating Management and Organisational Factors into Probabilistic Safety Assessment*. Reliability Engineering and Systems Safety, 38, 199-208.
- Maurino, D. E., Reason, J., Johnston, N. Lee, R.B. (1995) *Beyond Aviation Human Factors*. Ashgate: Vermont.
- Miller A.C., Merkhofer, M.W., Howard, R.A. (1976) *Development of Automated Aids for Decision Analysis*. Stanford Research Institute, Menlo Park, California.
- Merkhofer, M.W. (1990) *Using Influence Diagrams in Multivariate Utility Analysis: Improving Effectiveness through Improving Communication*. In Oliver, R.M. and Smith, J.A. (Eds.), *Influence Diagrams, Belief Nets and Decision*. Wiley: New York.
- McDonald, N., Corrigan, S., Daly, C., and Cromie, S. (2000) *Safety Management Systems and Safety Culture in Aircraft Maintenance Organisations* Safety Science 34 (2000) 151-176.
- Phillips, L.D., Embrey, D.E., Humphreys, P. & Selby, D.L. (1990) *A Socio-Technical Approach to Assessing Human Reliability*. In Oliver, R.M. and Smith, J.A. (Eds.), *Influence Diagrams, Belief Nets and Decision Making*. Wiley: New York.
- Reason, J (1997) *Managing the Risks of Organisational Accidents*. Ashgate: Vermont.
- Wright, K. V., Embrey, D.E. and Anderson, M (2000) *Getting at the Underlying Causes of SPADs*. Rail Professional, August 2000.